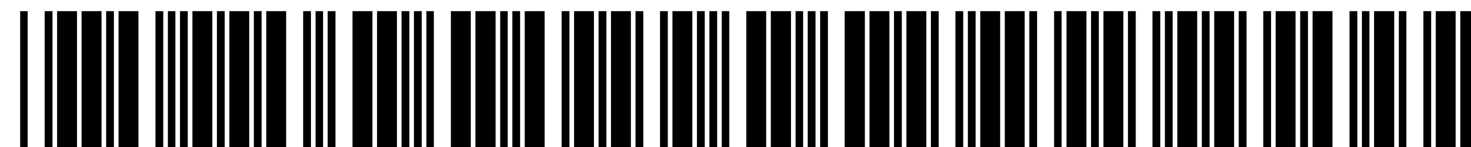

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Jun et al.

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(45) **Date of Patent: Oct. 24, 2017**

(54) **HYBRID DIODE DEVICE**

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CPC ***H02N 2/186*** (2013.01); ***H01L 29/2003*** (2013.01); ***H01L 29/205*** (2013.01);
(Continued)

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CPC H01L 41/113–41/1138; H01L 41/1132; H01L 41/0926; H01L 41/0933;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,541,818 B2 9/2013 Wu et al.
2006/0076855 A1 * 4/2006 Eriksen G01L 9/0042 310/344

(Continued)

FOREIGN PATENT DOCUMENTS

KR 10-2012-0074556 A 7/2012
KR 10-2013-00238010 A 3/2013

OTHER PUBLICATIONS

Marco Ferrari et al., "Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems", Sensors and Actuators A, vol. 142, No. 1, Mar. 10, 2008, pp. 329-335.

(Continued)

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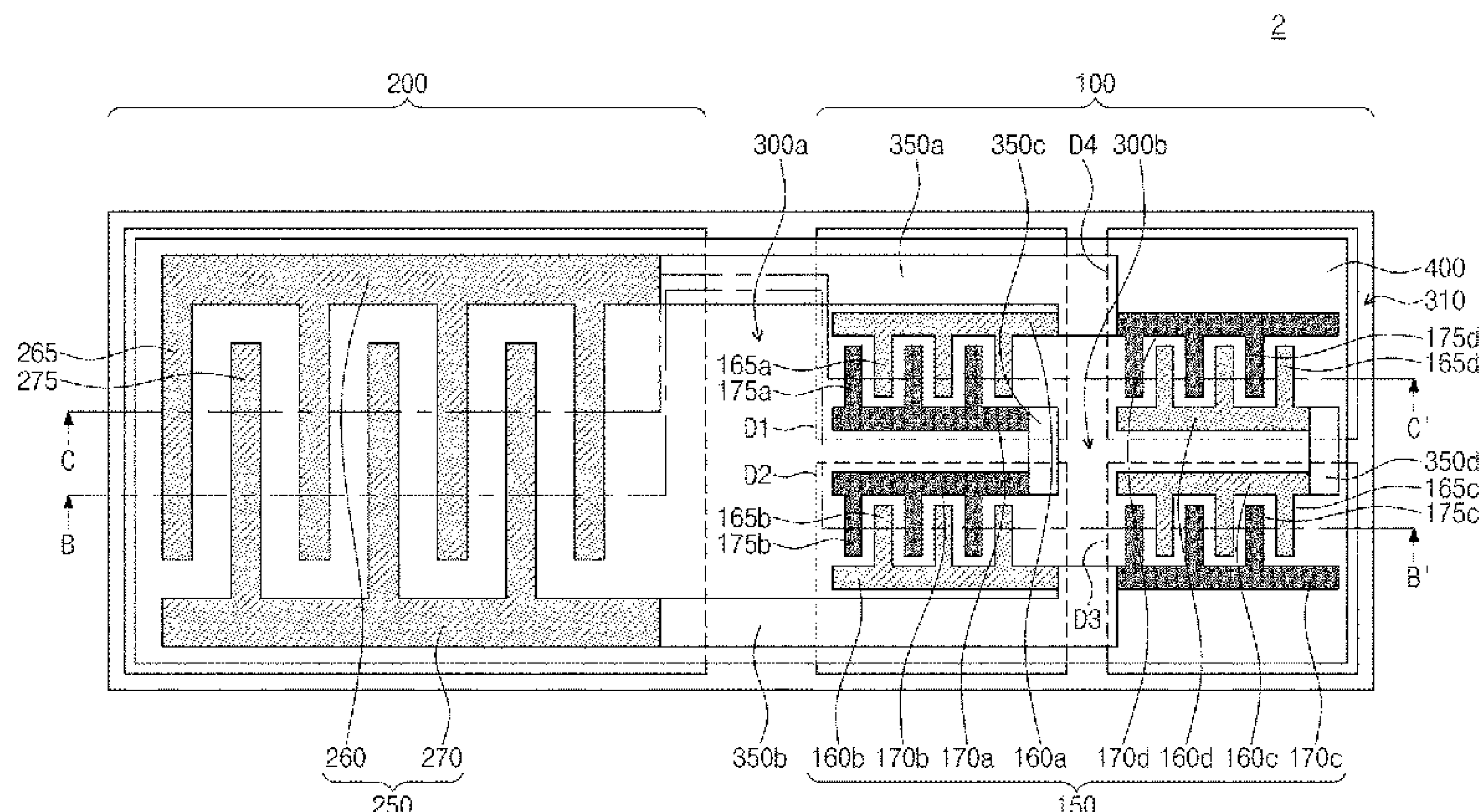
(57) **ABSTRACT**

Provided is a hybrid diode device. The hybrid diode device includes a first lower nitride layer disposed on a substrate and including a first 2-dimensional electron gas (2DEG) layer, a second lower nitride layer extending from the first lower nitride layer to the outside of the substrate and including a second 2DEG layer, a first upper nitride layer disposed on the first lower nitride layer, a second upper nitride layer disposed on the second lower nitride layer, a first cap layer disposed on the first upper nitride layer, a second cap layer disposed on the second upper nitride layer, a first electrode structure connected to the first lower nitride layer and the first cap layer; and a second electrode structure connected to the second lower nitride layer and the first
(Continued)



electrode structure. The second lower nitride layer generates electric energy through dynamic movement.

20 Claims, 7 Drawing Sheets

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H01L 29/872 (2006.01)
H01L 29/84 (2006.01)
H01L 29/20 (2006.01)
H01L 29/205 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 29/84*** (2013.01); ***H01L 29/872*** (2013.01); ***H01L 41/1136*** (2013.01)

(58) **Field of Classification Search**
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USPC 73/724; 438/49; 310/344; 257/301, 415
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2006/0217776 A1		9/2006	White et al.
2009/0174014 A1*		7/2009	Kunze B81B 3/0024 257/415
2011/0140579 A1		6/2011	Moon et al.
2013/0049539 A1		2/2013	Lee et al.
2014/0183669 A1*		7/2014	Xu G01C 19/5656 257/415

OTHER PUBLICATIONS

Ting-Fu Chang et al., "Low Turn-on voltage dual metal AlGaN/GaN Schottky barrier diode", Solid-State Electronics, vol. 105, Mar. 2015, pp. 12-15.

* cited by examiner

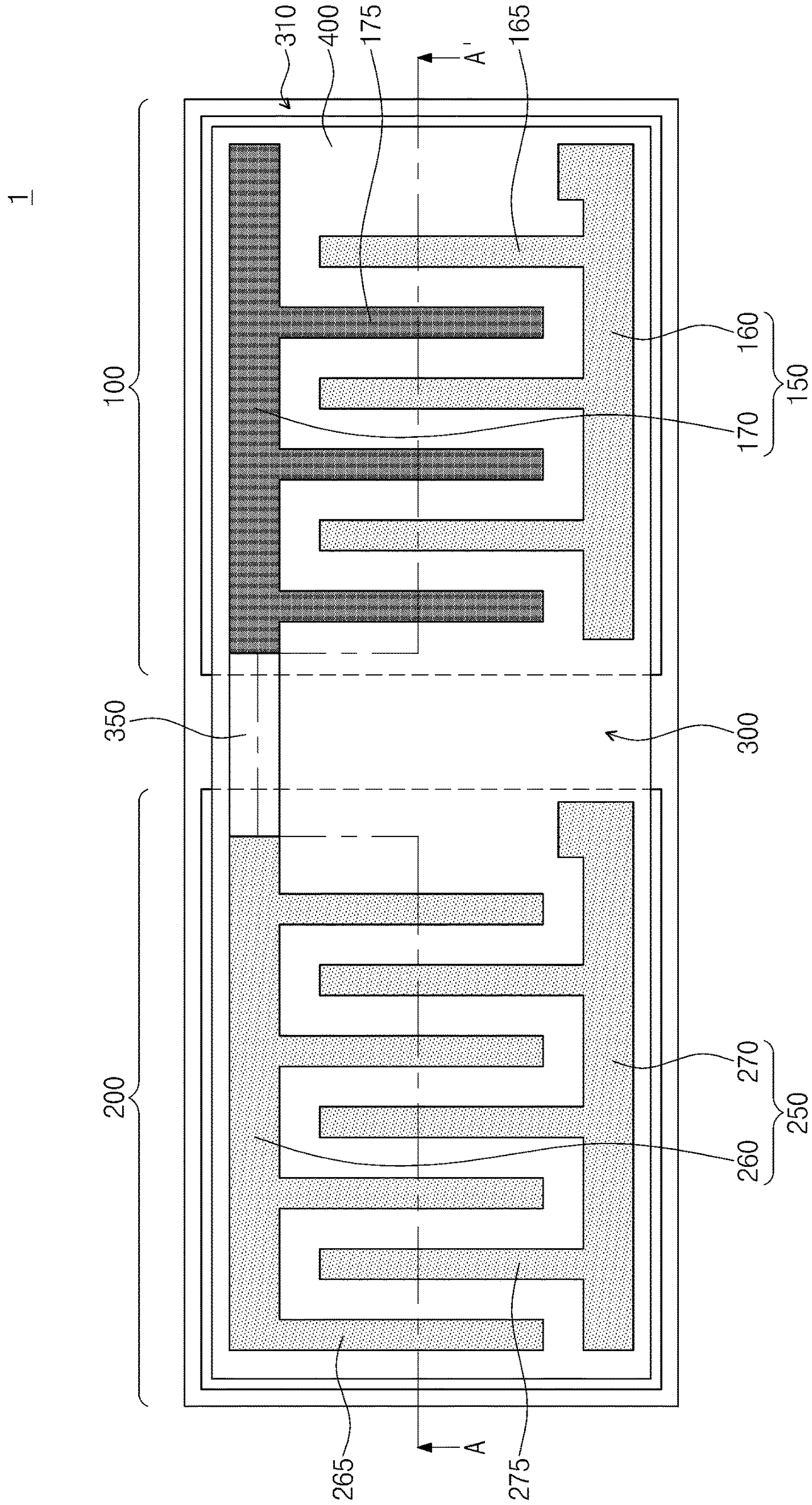


FIG. 1
1
100
200
300
310
350
400
175
165
160
170
150
270
260
250
265
275
A
A'

FIG. 2

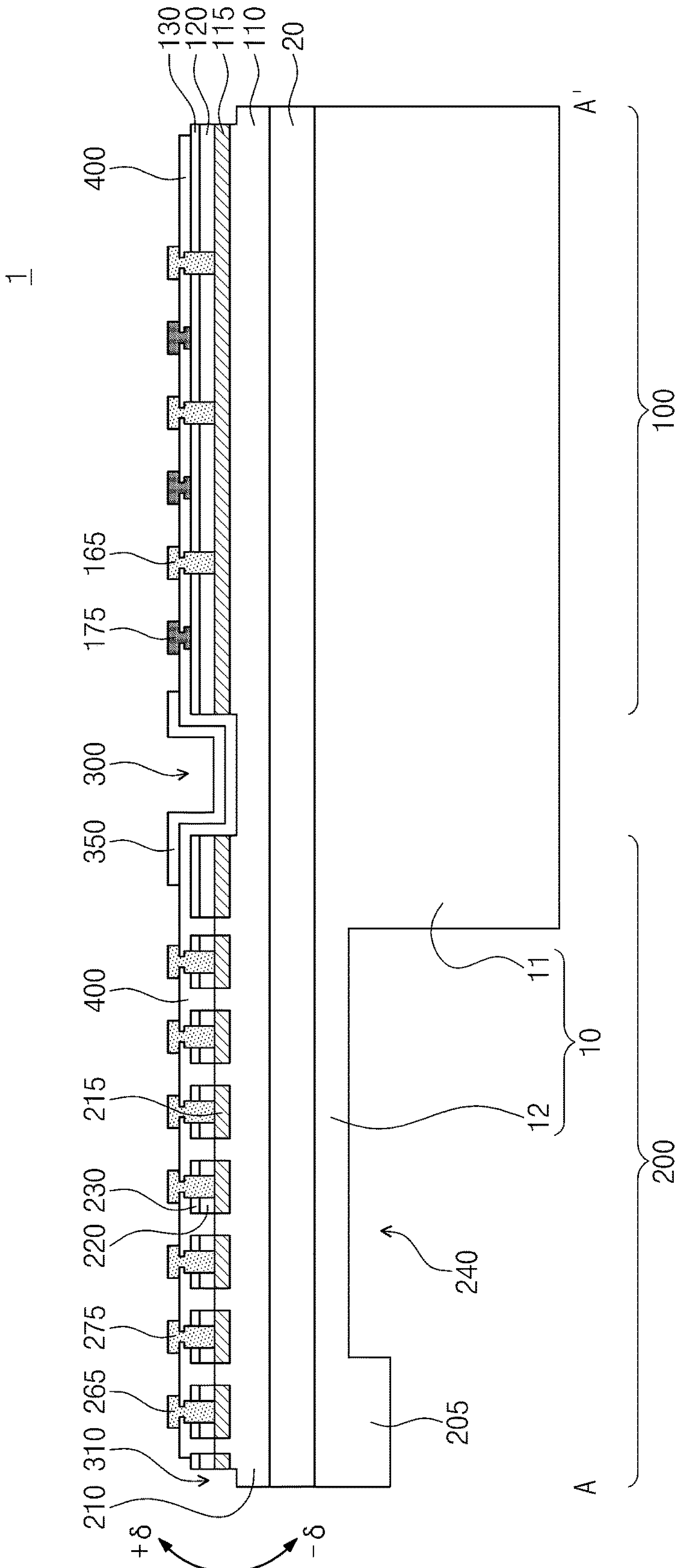
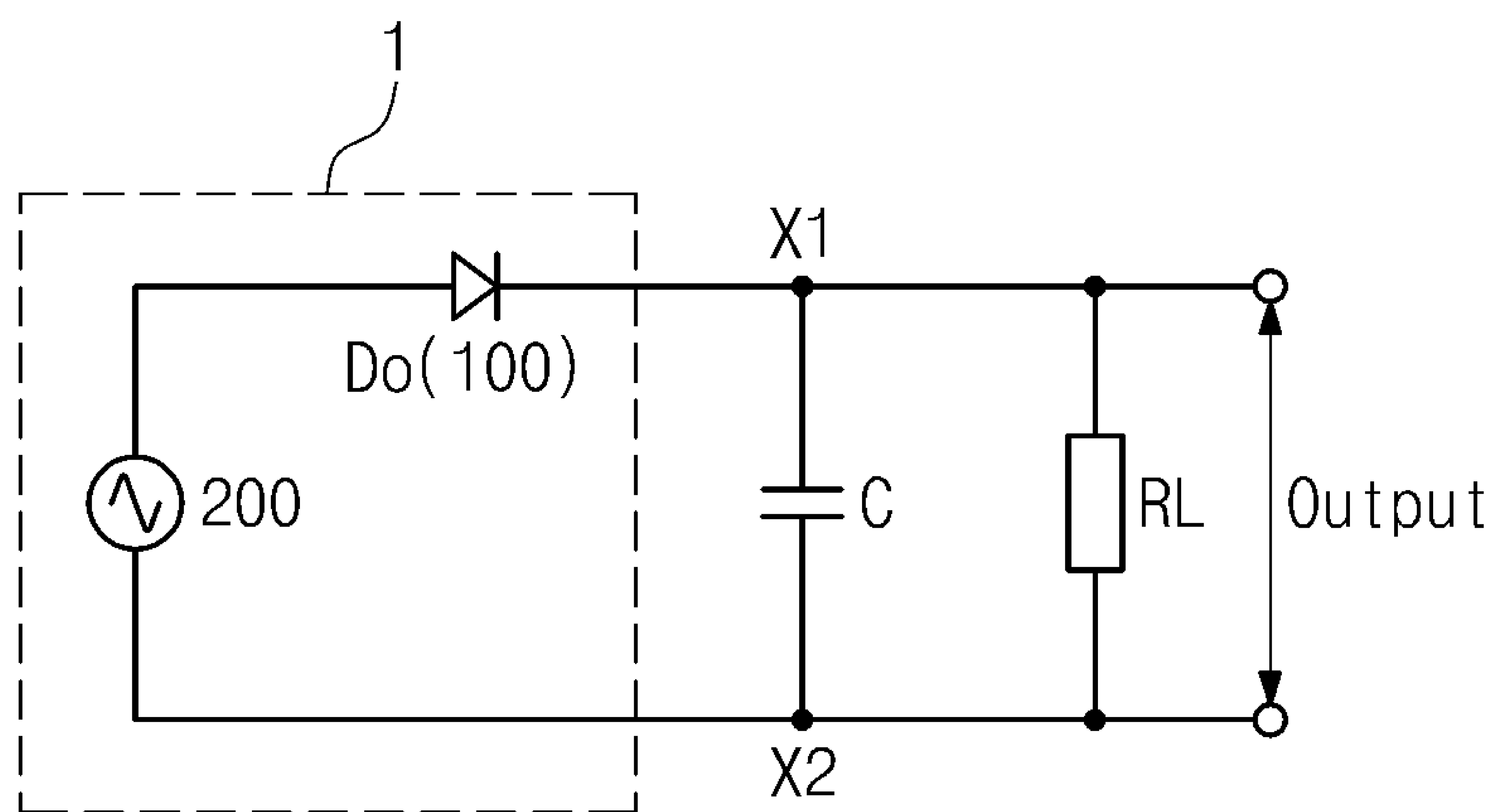


FIG. 3



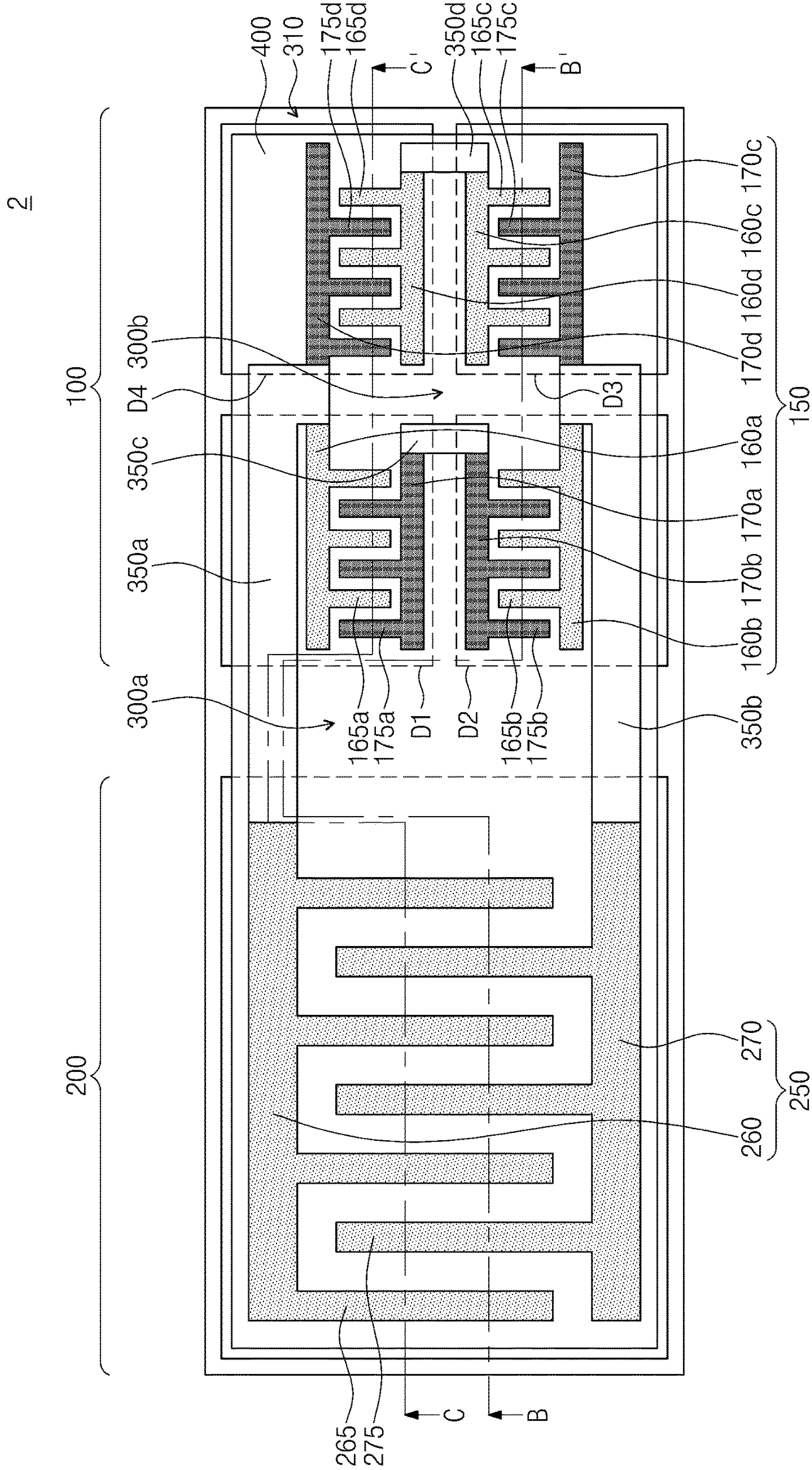


FIG. 4
2
100
200
150
250
400
310
175d
165d
350d
165c
175c
C'
B'
170c
160c
160d
170d
300b
D4
D3
350c
160a
170a
350a
170b
160b
300a
165a
175a
D1
D2
165b
175b
350b
270
260
265
275
C
B

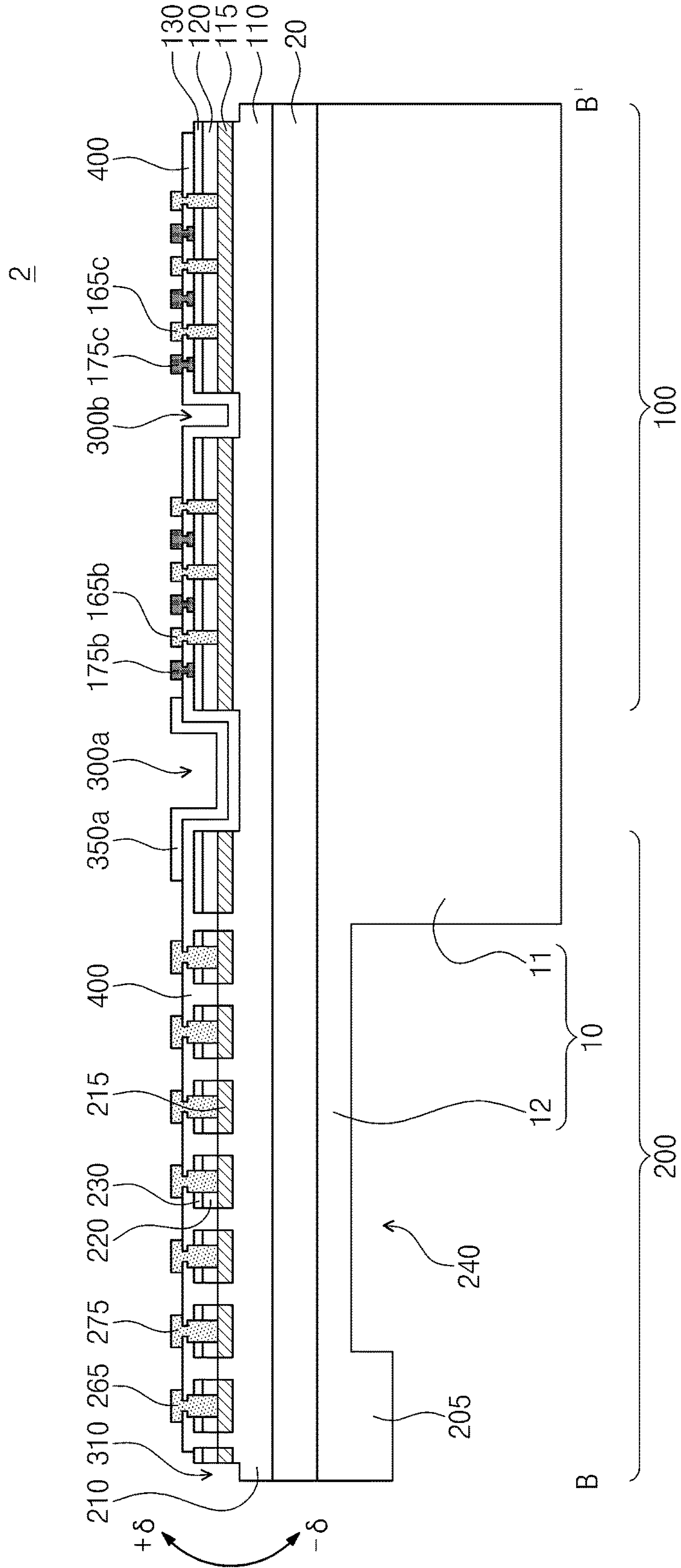


FIG. 5
2
130
120
115
110
20
B'
400
165c
175c
300b
165b
175b
300a
350a
100
11
10
400
215
230
220
12
200
240
275
265
310
210
205
B
+δ
-δ

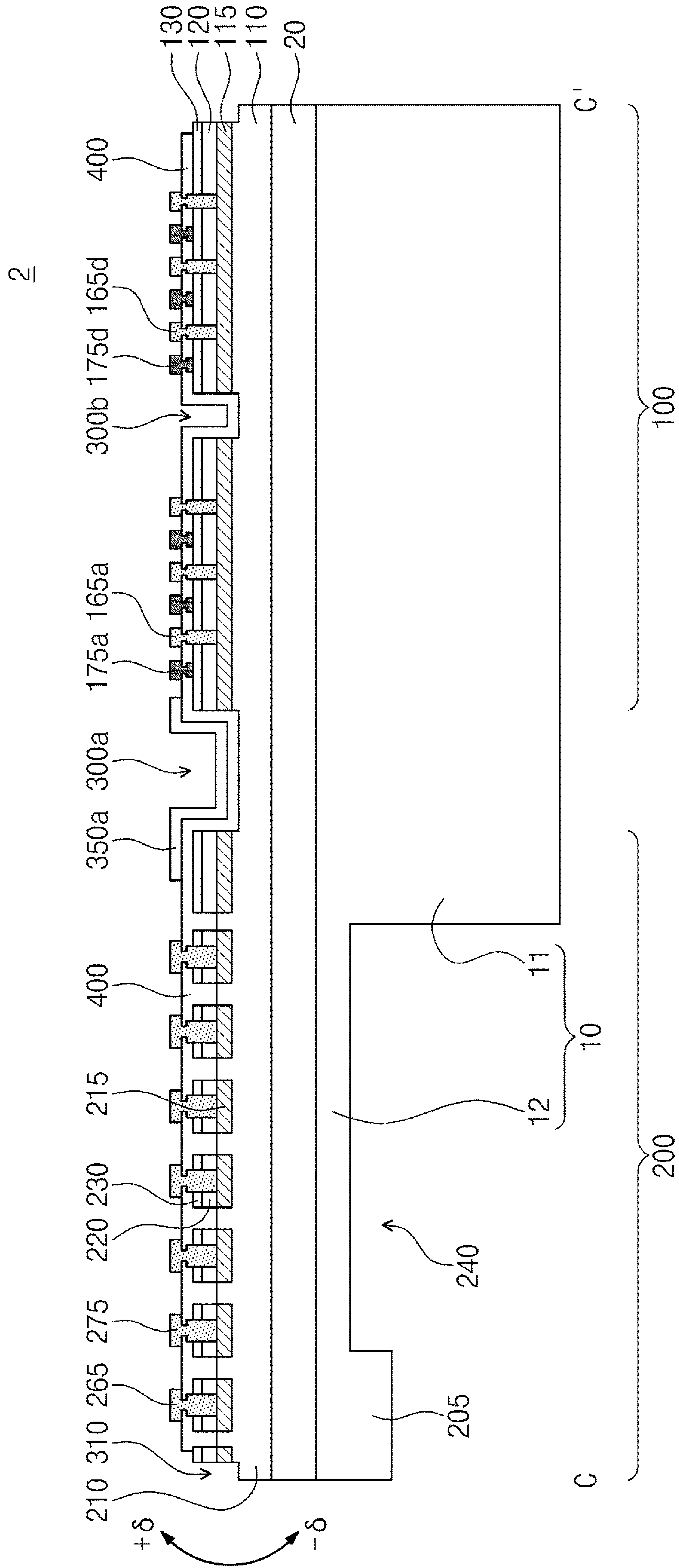
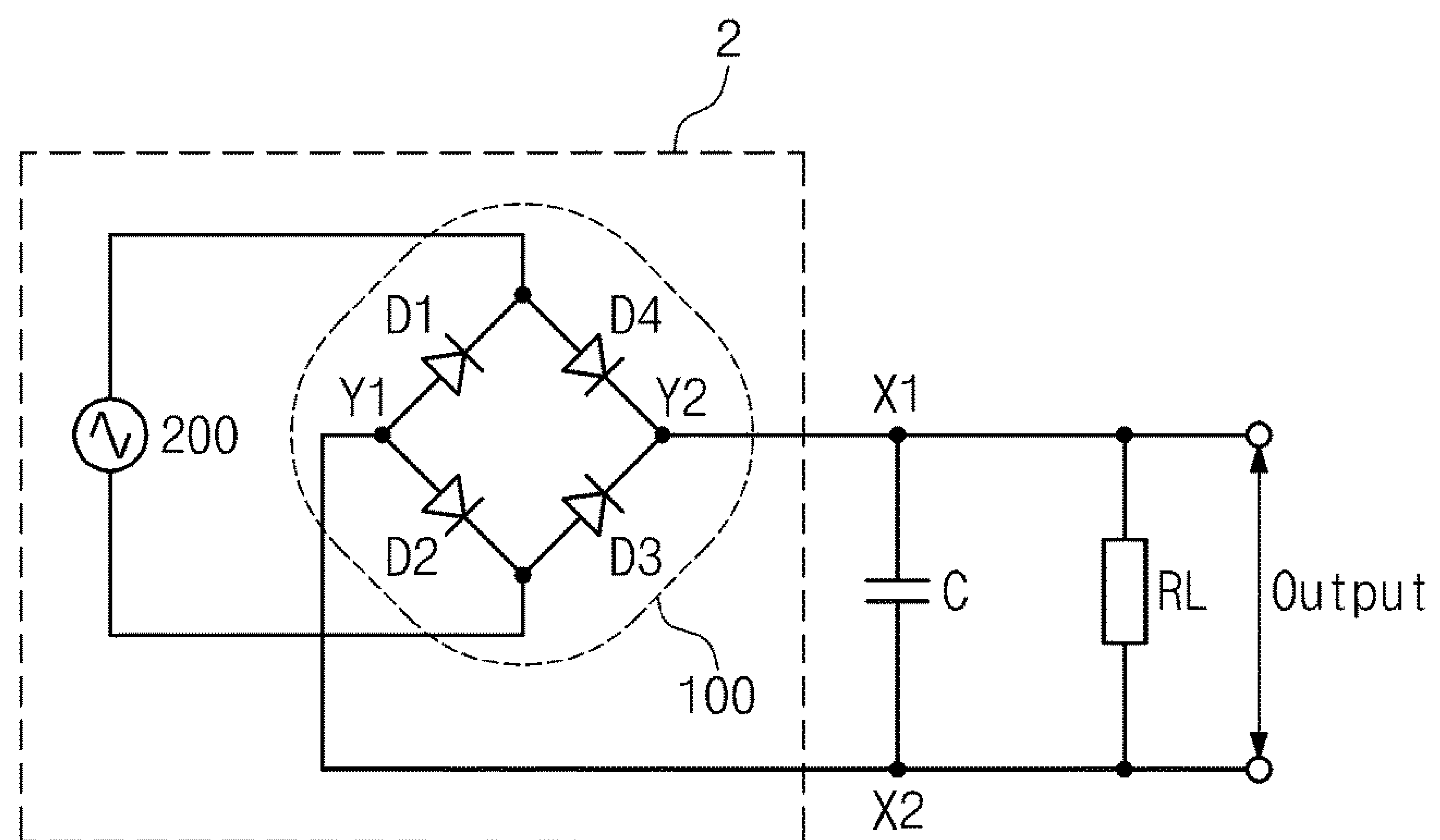


FIG. 6
2
130
120
115
110
20
C'
400
165d
175d
300b
165a
175a
300a
350a
100
400
215
230
220
275
265
310
210
+δ
-δ
11
10
12
200
240
205
C

FIG. 7



HYBRID DIODE DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This U.S. non-provisional patent application claims priority under 35 U.S.C. §119 of Korean Patent Application Nos. 10-2015-0159871, filed on Nov. 13, 2015, and 10-2016-0067678, filed on May 31, 2016, the entire contents of which are hereby incorporated by reference.

BACKGROUND

The present disclosure herein relates to a hybrid diode device, and more particularly, to a hybrid diode device in which a piezoelectric device and a diode device are integrated on one substrate.

Generally, electronic devices require a battery or a fixed power source as an operating power source. Particularly, the battery is required to be replaced according to periodic recharging or its lifetime. Recently, as electronic devices are developed in wireless and low-power types, energy harvesting-type micro power generators, which harvest electric energy from surrounding environments, are being studied.

Also, to supply the electric energy, which is generated by converting the surrounding environment energy, to electronic devices actually requiring the power as described above, a rectifier device that converts the generated electric energy having a predetermined waveform into direct current or a rectifier circuit component combined therewith are additionally required.

SUMMARY

The present disclosure provides a hybrid diode device in which a piezoelectric device and a diode device are integrated on one substrate. Thus, a self-power providing hybrid diode device may be provided.

The present disclosure also provides a hybrid diode device including a piezoelectric device and a diode device, which share a gallium nitride-based nitride layer formed of a piezoelectric material.

The present disclosure also provides a diode device capable of converting alternating current-type electric energy provided by a piezoelectric device into direct current-type electric energy.

An embodiment of the inventive concept provides a hybrid diode device including: a first lower nitride layer disposed on a substrate and including a first 2-dimensional electron gas (2DEG) layer; a second lower nitride layer extending from the first lower nitride layer to the outside of the substrate and including a second 2DEG layer; a first upper nitride layer disposed on the first lower nitride layer; a second upper nitride layer disposed on the second lower nitride layer; a first cap layer disposed on the first upper nitride layer; a second cap layer disposed on the second upper nitride layer; a first electrode structure connected to the first lower nitride layer and the first cap layer; and a second electrode structure connected to the second lower nitride layer and the first electrode structure, wherein the second lower nitride layer generates electric energy through dynamic movement.

In an embodiment, the first 2DEG layer may be spaced apart and electrically insulated from the second 2DEG layer.

In an embodiment, each of the first and second lower nitride layers may include gallium nitride (GaN) as a gallium nitride-based material.

In an embodiment, the second upper nitride layer may include nitride layer patterns exposing a portion of the second lower nitride, and the second 2DEG layer is provided on an area on which the second lower nitride layer contacts the nitride layer patterns.

In an embodiment, the second 2DEG layer may be discontinuously provided on an interface between the second lower nitride layer and the second upper nitride layer in a first direction, and the first direction may be perpendicular to a direction that is directed from the second upper nitride layer toward the second lower nitride layer.

In an embodiment, the second electrode structure may pass through each of the nitride layer patterns to contact the second 2DEG layer.

In an embodiment, the first electrode structure may include: a first electrode electrically connected to the first 2DEG layer in the first lower nitride layer; and a second electrode connected to the first cap layer, and a second electrode structure may include a third electrode and a fourth electrode, which are electrically connected to the second 2DEG layer in the second lower nitride layer.

In an embodiment, each of the first electrode, the third electrode, and the fourth electrode may be an ohmic electrode, and the second electrode may be a Schottky electrode, wherein the third electrode is connected to the second electrode through a connection pad, and the first electrode and the fourth electrode are connected to an external circuit.

In an embodiment, the first electrode may be an ohmic electrode that is provided in plurality, and the second electrode may be a Schottky electrode that is provided in plurality, wherein the first electrodes and the second electrodes constitute a bridge circuit.

In an embodiment, the first electrodes may include a first ohmic electrode, a second ohmic electrode, a third ohmic electrode, and a fourth ohmic electrode, the second electrodes may include a first Schottky electrode, a second Schottky electrode, a third Schottky electrode, and a fourth Schottky electrode, and a pair of first ohmic electrode and first Schottky electrode, a pair of second ohmic electrode and second Schottky electrode, a pair of third ohmic electrode and third Schottky electrode, and a pair of fourth ohmic electrode and fourth Schottky electrode may constitute first to fourth diodes, respectively.

In an embodiment, an isolation area may be provided between the first to fourth diodes to respectively divide the first to fourth diodes into each other.

In an embodiment, the first diode and the fourth diode may be connected to the third electrode through a first connection pad, the second diode and the third diode may be connected to the fourth electrode through a second connection pad, and the first diode and the second diode, and the third diode and the fourth diode may be connected to an external circuit through a third connection pad and a fourth connection pad, respectively.

In an embodiment of the inventive concept, a hybrid diode device includes: a substrate including a body part and a cantilever; a lower nitride layer disposed on the substrate and including a 2-dimensional electron gas (2DEG) layer; an upper nitride layer disposed on the lower nitride layer; a first isolation area configured to divide the 2DEG layer into a first 2DEG layer and a second 2DEG layer and divide the upper nitride layer into a first upper nitride layer and a second upper nitride layer; a first electrode structure connected to the first 2DEG layer and the first upper nitride layer; and a second electrode structure connected to the second 2DEG layer, wherein the second 2DEG layer and the second upper nitride layer are disposed on the cantilever, and the second

electrode structure transfers electric energy, which is generated by a change of strain applied to the lower nitride layer, to the first electrode structure.

In an embodiment, the first isolation area may be recessed from the upper nitride layer toward the lower nitride layer.

In an embodiment, the hybrid diode device may further include a connection pad disposed on the first isolation area, wherein the connection pad connects the first electrode structure to the second electrode structure.

In an embodiment, the hybrid diode device may further include a second isolation area which is recessed from the first upper nitride layer toward the first 2DEG layer to divide each of the first 2DEG layer and the first upper nitride layer into four parts, wherein the first electrode structure includes a pair of ohmic electrode and Schottky electrode, which are respectively connected to the divided first 2DEG layers and the divided first upper nitride layers.

In an embodiment, the pair of ohmic electrode and Schottky electrode, which constitutes one diode, may be provided in four, and the ohmic electrodes and the Schottky electrodes may constitute a bridge circuit.

In an embodiment, the hybrid diode device may further include a cap layer disposed on a top surface of the upper nitride layer, wherein the cap layer is divided by the first isolation area and the second isolation area.

In an embodiment, the hybrid diode device may further include a passivation layer disposed on a top surface of the cap layer.

In an embodiment, the hybrid diode device may further include a peripheral isolation area on edges of the lower nitride layer and the upper nitride layer, which is recessed in a direction that is directed from the upper nitride layer to the lower nitride layer.

In an embodiment, the hybrid diode device may further include a proof mass disposed on an edge of the cantilever facing the substrate, wherein an opened space in which the cantilever is movable is provided below the cantilever.

BRIEF DESCRIPTION OF THE FIGURES

The accompanying drawings are included to provide a further understanding of the inventive concept, and are incorporated in and constitute a part of this specification. The drawings illustrate exemplary embodiments of the inventive concept and, together with the description, serve to explain principles of the inventive concept. In the drawings:

FIG. **1** is a plan view of a hybrid diode device according to an embodiment of the inventive concept;

FIG. **2** is a cross-sectional view taken along line A-A' of FIG. **1**;

FIG. **3** is a circuit diagram of the hybrid diode device according to an embodiment of the inventive concept;

FIG. **4** is a plan view of a hybrid diode device according to an embodiment of the inventive concept;

FIG. **5** is a cross-sectional view taken along line B-B' of FIG. **4**;

FIG. **6** is a cross-sectional view taken along line C-C' of FIG. **4**; and

FIG. **7** is a circuit diagram of the hybrid diode device according to an embodiment of the inventive concept.

DETAILED DESCRIPTION

Advantages and features of the present disclosure, and implementation methods thereof will be clarified through following embodiments described with reference to the accompanying drawings. However, the present disclosure may be embodied in different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art. Further, the present invention is only defined by scopes of claims. Like reference symbols refer to like elements throughout.

Additionally, the embodiments described in this specification will be explained with reference to the cross-sectional views and/or plan views as ideal exemplary views of the present disclosure. In the figures, the thicknesses of layers and regions are exaggerated for effective description of the technical contents. Accordingly, shapes of the exemplary views may be modified according to manufacturing techniques and/or allowable errors. Therefore, the embodiments of the inventive concept are not limited to the specific shape illustrated in the exemplary views, but may include other shapes that may be created according to manufacturing processes. For example, an etched region illustrated as a right angle may have rounded or predetermined curved features. Therefore, areas exemplified in the drawings have general properties, and shapes of areas exemplified in the drawing are used to illustrate a specific shape of a device region. Thus, this should not be construed as limited to the scope of the present disclosure.

FIG. **1** is a plan view of a hybrid diode device according to an embodiment of the inventive concept, and FIG. **2** is a cross-sectional view taken along line A-A' of FIG. **1**.

Referring to FIGS. **1** and **2**, a hybrid diode device **1** may include a diode device **100** and a piezoelectric device **200**. The diode device **100** may be electrically connected to the piezoelectric device **200**. The piezoelectric device **200** may generate electric energy by environmental changes such as vibration and pressure variation. For example, the piezoelectric device **200** may vibrate at a frequency of several Hz to several tens of kHz. The diode device **100** may rectify and convert alternating current-type electric energy generated by the piezoelectric device **200** into direct current-type electric energy. For example, the diode device **100** may perform half-wave rectification in which reverse current of alternating current electric energy generated by the piezoelectric device **200** is blocked, and only forward current flows. The diode device **100** and the piezoelectric device **200** may be disposed on a substrate **10**. For example, the substrate **10** may include one of sapphire, silicon, gallium nitride (GaN), and silicon carbide (SiC). The substrate **10** may include a body part **11** on which the diode device **100** is disposed and a cantilever **12** on which the piezoelectric device **200** is disposed. The cantilever **12** may have a thickness less than that of the body part **11**. Thus, the cantilever **12** having an end fixed to the body part **11** may vibrate. A thickness of the cantilever **12** may be determined according to a thickness thereof to be etched. For example, the body part **11** may have a thickness of several tens of μm to several mm, and the cantilever **12** may have a thickness of several μm to several tens μm. A passivation layer **400** may be provided on the diode device **100** and the piezoelectric device **200** to protect the diode device **100** and the piezoelectric device **200**. The hybrid diode device **1** may be embedded in a package (not shown) or a can (not shown) for protecting the hybrid diode device **1** against external environments.

The diode device **100** may include a first lower nitride layer **110**, a first upper nitride layer **120**, a first cap layer **130**, and a first electrode structure **150**. The first lower nitride layer **110** may contact the substrate **10**. The first lower nitride layer **110** may include gallium nitride (GaN). A first

2-dimensional electron gas (2DEG) layer **115** may be provided in the first lower nitride layer **110**. The first 2DEG layer **115** may function as a channel through which current flows because electron gas having high density exists in the first 2DEG layer **115**. A buffer layer **20** may be disposed between the substrate **10** and the first lower nitride layer **110**. The buffer layer **20** may be defined as a portion of the substrate **10**. The buffer layer **20** may compensate a difference in lattice constant between the substrate **10** and the first lower nitride layer **110**.

The first upper nitride layer **120** may be disposed on the first lower nitride layer **110**. The first upper nitride layer **120** may form a heterojunction structure with the first lower nitride **110**. The first upper nitride layer **120** may include aluminum gallium nitride (AlGaN).

The first cap layer **130** may be disposed on the first upper nitride layer **120**. The first cap layer **130** may include gallium nitride (GaN), indium gallium nitride (InGaN), or aluminum nitride (AlN). The first cap layer **130** may be a single layer or a composite layer constituted by the above-described several kinds of layers. Also, the first cap layer **130** may reduce leakage current through a surface of the first upper nitride layer **120**. According to an embodiment, an electrical insulation layer such as alumina (Al_2O_3), silicon oxide (SiO_2), silicon nitride (Si_3N_4) or hafnium oxide (HfO_2) may be additionally disposed on the first cap layer **130**.

The passivation layer **400** may be disposed on the first cap layer **130**. The passivation layer **400** may protect the diode device **100**.

The first electrode structure **150** may include a first electrode **160** and a second electrode **170**. The first electrode **160** may pass through the first upper nitride layer **120** and the first cap layer **130** to directly contact the first lower nitride **110**. Since the first 2DEG layer **115** is disposed on an interface between the first upper nitride layer **120** and the first lower nitride layer **110**, the first electrode **160** may directly contact the first 2DEG layer **115**. The second electrode **170** may pass through the passivation layer **400** to directly contact the first cap layer **130**. The first electrode **160** and the second electrode **170** may be spaced apart from each other. The first electrode **160** may be an ohmic electrode ohmic-contacting the first 2DEG layer **115**, and the second electrode **170** may be a Schottky electrode Schottky-contacting the first cap layer **130**. The ohmic electrode may be a cathode, and the Schottky electrode may be an anode. The first electrode **160** and the second electrode **170** may constitute a diode. For example, the anode may include nickel (Ni) or gold (Au), and the cathode may be an alloy including at least one of nickel (Ni), gold (Au), aluminum (Al), titanium (Ti) or molybdenum (Mo). The first electrode **160** may have an end connected to an external circuit, and the second electrode **170** may have an end electrically connected to the piezoelectric device **200**.

The first electrode **160** and the second electrode **170** may respectively have a plurality of first extension parts **165** and second extension parts **175**, which are exposed on the passivation layer **400**. The first extension parts **165** may extend toward the second electrode **170**, and the second extension parts **175** may extend toward the first electrode **160**. The first extension parts **165** and the second extension parts **175** may be alternately disposed in one direction. The first extension parts **165** and the second extension parts **175** may be spaced apart from each other.

The piezoelectric device **200** may include a second lower nitride layer **210**, a second upper nitride layer **220**, a second cap layer **230**, and a second electrode structure **250**.

The second lower nitride layer **210** may be connected to the first lower nitride layer **110**. The second lower nitride layer **210** may extend from the first lower nitride layer **110** to the outside of the substrate **10**. The second lower nitride layer **210** may include gallium nitride (GaN). A second 2-dimensional electron gas (2DEG) layer **215** may be provided in the second lower nitride layer **210**. The second 2DEG layer **215** may function as a channel through which current flows because electron gas having high density exists in the second 2DEG layer **215**. The second lower nitride layer **210** may function as a piezoelectric material. Dynamic movement of the cantilever **12** may be induced by environmental changes such as vibration and pressure variation, and then a change of strain may be applied to the second lower nitride layer **210**. Accordingly, electric energy may be generated by piezoelectric conversion in the second lower nitride layer **210**, and the generated electric energy may be transferred to the second electrode structure **250** by the second 2DEG layer **215**.

The buffer layer **20** may be disposed on a bottom surface of the second lower nitride layer **210**. The buffer layer **20** may support the second lower nitride layer **210**.

The piezoelectric device **200** may be disposed on the cantilever **12** extending outward from the body part **11** of the substrate **10**. For example, a proof mass **205** may be disposed on a bottom surface of the buffer layer **20**. The proof mass **205** may be disposed on a distal end of the cantilever **12** facing the body part **11**. The proof mass **205** may facilitate the vibration of the cantilever **12**. The proof mass **205** may be formed by removing a portion of the substrate **10**. Thus, the proof mass **205** may have the same material as the substrate **10**. For example, the proof mass **205** may include one of sapphire, silicon, gallium nitride (GaN), and silicon carbide (SiC).

An opened space **240** may be provided below the second lower nitride layer **210**. The opened space **240** may be formed by removing a portion of the substrate **10**. The opened space **240** may provide a space in which the cantilever (corresponding to the piezoelectric device **200**) vibrates. Thus, the opened space **240** may have a height greater than an amplitude ($\pm\delta$) at which the cantilever **12** vibrates. The height of the opened space **240** may be determined by the removed thickness of the substrate **10**.

The second upper nitride layer **220** may be disposed on the second lower nitride layer **210**. The second upper nitride layer **220** may form a heterojunction structure with the second lower nitride layer **210**. The second upper nitride layer **220** may include aluminum gallium nitride (AlGaN). For example, the second upper nitride layer **220** may include nitride layer patterns exposing a portion of the second lower nitride layer **210**. The second 2DEG layer **215** may be provided on only area on which the nitride layer patterns contact the second lower nitride layer **210**. That is, the second 2DEG layer **215** may be discontinuously provided on an interface between the second lower nitride layer **210** and the nitride layer patterns in a first direction. The first direction may be a direction perpendicular to a direction that is directed from the second upper nitride layer **220** toward the second lower nitride layer **210**.

The second cap layer **230** may be disposed on the second upper nitride layer **220**. For example, the second cap layer **230** may be disposed on the nitride layer patterns. The second cap layer **230** may include gallium nitride (GaN), indium gallium nitride (InGaN), or aluminum nitride (AlN). The second cap layer **230** may be a single layer or a composite layer constituted by several kinds of layers. The second cap layer **230** may reduce leakage current through a

surface of the second upper nitride layer **220**. According to an embodiment, electrical insulation layers such as alumina (Al_2O_3), silicon oxide (SiO_2), silicon nitride (Si_3N_4) or hafnium oxide (HfO_2) may be additionally disposed on the second cap layer **230**.

The passivation layer **400** may be disposed on the second cap layer **230** and between the nitride layer patterns and the second cap layers **230**. Since the passivation layer **400** may be provided between the nitride layer patterns to electrically insulate the nitride layer patterns from each other.

The second electrode structure **250** may include a third electrode **260** and a fourth electrode **270**. The third electrode **260** and the fourth electrode **270** may pass through the second upper nitride layer **220** to contact the second lower nitride layer **210**. Since the second 2DEG layer **215** may be disposed on an interface between the second upper nitride layer **220** and the second lower nitride layer **210**, the third electrode **260** and the fourth electrode **270** may directly contact the second 2DEG layer **215**. The second 2DEG layer **215** may be connected to the second electrode structure **250** to function as an counter electrode for the piezoelectric transduction. The third electrodes **260** and the fourth electrodes **270** may be disposed to correspond to the second upper nitride layers (the nitride layer patterns) **220**, which are patterned and divided in plurality, respectively. That is, one of the third electrode **260** or the fourth electrode **270** may be disposed on one of the nitride layer patterns, and the third electrodes **260** may be electrically insulated from the fourth electrodes **270** by the passivation layer **400** disposed between nitride layer patterns.

The third electrode **260** and the fourth electrode **270** may be ohmic electrodes ohmic-contacting the second 2DEG layer **215**. For example, the third electrode **260** and the fourth electrode **270** may be alloys including at least one of nickel (Ni), gold (Au), aluminum (Al), titanium (Ti) or molybdenum (Mo). The third electrode **260** may have an end electrically connected to the diode device **100**, and the fourth electrode **270** may have an end connected to an external circuit.

The third electrode **260** and the fourth electrode **270** may have third extension parts **265** and fourth extension parts **275**, which are disposed on the passivation layer **400**, respectively. The third extension parts **265** may extend toward the fourth electrode **270**, and the fourth extension parts **275** may extend toward the third electrode **260**. The third extension parts **265** and the fourth extension parts **275** may be alternately disposed in one direction. The third extension parts **265** and the fourth extension part **275** may be spaced apart from each other, respectively.

An isolation area **300** may be disposed between the diode device **100** and the piezoelectric device **200**. The isolation area **300** may be an area recessed toward the substrate **10** on the first upper nitride layer **120** or the second upper nitride layer **220**. The isolation area **300** may be formed through mesa-etching. The isolation area **300** may isolate the first upper nitride layer **120** from the second upper nitride layer **220** and isolate the first 2DEG layer **115** from the second 2DEG layer **215**. Thus, the diode device **100** may be electrically insulated and spatially isolated from the piezoelectric device **200**.

The passivation layer **400** may be disposed on the isolation area **300**, and a connection pad **350** may be disposed on the passivation layer **400**. The connection pad **350** may electrically connect the first electrode structure **150** to the second electrode structure **250**. Particularly, the connection pad **350** may connect the second electrode **170** of the first electrode structure **150** to the third electrode **260** of the second electrode structure **250**.

A peripheral isolation area **310** may be provided on edges of the first and second lower nitride layers **110** and **210** and the first and second upper nitride layers **120** and **220**. The peripheral isolation area **310** may be an area recessed in a direction that is directed from the first and second upper nitride layers **120** and **220** to the first and second lower nitride layers **110** and **210**. The peripheral isolation area **310** may be an area in which the first and second 2DEG layers **115** and **215**, which are disposed around the interfaces between the first and second lower nitride layers **110** and **210** and the first and second upper nitride layers **120** and **220**, are removed. Thus, the hybrid diode device **1** may be electrically insulated from other semiconductor devices.

According to an embodiment of the inventive concept, a change of strain may be applied to the second lower nitride layer **210** of the piezoelectric device **200** by environmental changes such as vibration and pressure variation. Since the second lower nitride layer **210** includes a piezoelectric material, electric energy may be generated by extension and contraction of the piezoelectric material. The generated electric energy may be transferred to the second electrode structure **250** through the second 2DEG layer **215**, and the second electrode structure **250** may supply the electric energy to the diode device **100** through the first connection pad **350**.

According to an embodiment of the inventive concept, the diode device **100** and the piezoelectric device **200** may be disposed on the one substrate **10**. The hybrid diode device **1** may not supply electric energy supplied from an external power source, but may supply the electric energy generated from the piezoelectric device **200** to the diode device **100**. Thus, in the hybrid diode device **1** according to an embodiment of the inventive concept, the self-power supply may be possible to reduce the number of processes for electrically connecting the power source to the diode device, thereby increasing energy conversion efficiency, enabling miniaturization, and reducing manufacturing cost of the hybrid diode device.

FIG. **3** is a circuit diagram of the hybrid diode device according to an embodiment of the inventive concept.

Referring to FIGS. **1** to **3**, the piezoelectric device **200** may be an input power source generating electric energy, and the diode device **100** may be a half-wave rectification circuit which rectifies and converts the alternating current-type electric energy generated by the piezoelectric device **200** into the direct current type. The first electrode **160** which is the ohmic electrode and the second electrode **170** which is the Schottky electrode may form a Schottky diode Do. The first electrode **160** may have an end connected to a first point X1, and the fourth electrode **270** may have an end connected to a second point X2. An output terminal may be disposed between the first point X1 and the second point X2. Positive electric energy generated from the piezoelectric device **200** may pass through the Schottky diode Do and be applied to the output terminal. However, negative electric energy generated from the piezoelectric device **200** may not pass through the Schottky diode Do. Thus, the positive electric energy converted into the direct current by the diode device **100** may be transferred to the output terminal to supply the power to a capacitor C and a load R_L. Since the piezoelectric device **200** functioning as the input power source and the diode device **100** functioning as the rectification circuit are integrated on the substrate to from the hybrid diode device **1**, the circuit may be minimized in

whole size, and the number of electrical connection processes may be reduced to increase the energy conversion efficiency.

FIG. **4** is a plan view of a hybrid diode device according to an embodiment of the inventive concept, FIG. **5** is a cross-sectional view taken along line B-B' of FIG. **4**, and FIG. **6** is a cross-sectional view taken along line C-C' of FIG. **4**. Descriptions duplicated with those of FIGS. **1** and **2** will be omitted for conciseness of description. Since descriptions with respect to the piezoelectric device **200** are the same as those the piezoelectric device of FIGS. **1** and **2**, its description will be omitted.

Referring to FIGS. **4** to **6**, a hybrid diode device **2** may include a diode device **100** and a piezoelectric device **200**. The piezoelectric device **200** may generate electric energy by environmental changes such as vibration and pressure variation, and the diode device **100** may rectify and convert alternating current-type electric energy generated by the piezoelectric device **200** into direct current-type electric energy. For example, the diode device **100** may perform a full-wave rectification in which all the alternating current-type electric energy generated by the piezoelectric device **200** is converted into the direct current. The diode device **100** may be spatially isolated and electrically insulated from the piezoelectric device **200** by a first isolation area **300***a*. A first connection pad **350***a* and a second connection pad **350***b* may be disposed on the first isolation area **300***a*. The diode device **100** may be electrically connected to the piezoelectric device **200** by the first connection pad **350***a* and the second connection pad **350***b*. Also, the hybrid diode device **2** may be electrically insulated from other semiconductor devices through a peripheral isolation area **310**. The detailed connection relationship will be described later.

The diode device **100** may include a second isolation area **300***b* that divides each of a first lower nitride layer **110**, a first upper nitride layer **120**, and a first cap layer **130** into four parts, respectively. The second isolation area **300***b* may be an area recessed from the first cap layer **130** toward the first lower nitride layer **110**. That is, the second isolation area **300***b* may divide a first 2-dimensional electron gas (2DEG) layer **115** in the first lower nitride layer **110** into four parts. Accordingly, the divided first 2DEG layers **115** may be insulated from each other.

A first electrode structure **150** may be connected to the divided first 2DEG layers **115** and the cap layers **130** to from a bridge circuit. The first electrode structure **150** may include first electrodes **160***a*, **160***b*, **160***c*, and **160***d* which are ohmic electrodes and second electrodes **170***a*, **170***b*, **170***c*, and **170***d* which are Schottky electrodes. The first electrodes **160***a*, **160***b*, **160***c*, and **160***d* may pass through the first cap layer **130** and the first upper nitride layer **120** and be connected to the first 2DEG layer **115**, and the second electrodes **170***a*, **170***b*, **170***c*, and **170***d* may be connected to the first cap layer **130**. The first electrodes **160***a*, **160***b*, **160***c*, and **160***d* may include a first ohmic electrode **160***a*, a second ohmic electrode **160***b*, a third ohmic electrode **160***c*, and a fourth ohmic electrode **160***d*. The second electrodes **170***a*, **170***b*, **170***c*, and **170***d* may include a first Schottky electrode **170***a*, a second Schottky electrode **170***b*, a third Schottky electrode **170***c*, and a fourth Schottky electrode **170***d*. A pair of first ohmic electrode **160***a* and first Schottky electrode **170***a*, a pair of second ohmic electrode **160***b* and second Schottky electrode **170***b*, a pair of third ohmic electrode **160***c* and third Schottky electrode **170***c*, and a pair of fourth ohmic electrode **160***d* and fourth Schottky electrode **170***d* may constitute first to fourth diodes D**1**, D**2**, D**3**, and D**4**, respectively.

Each of the first electrodes **160***a*, **160***b*, **160***c*, and **160***d* and the second electrodes **170***a*, **170***b*, **170***c*, and **170***d* may have a plurality of extension parts spaced apart from each other on a passivation layer **400**. The first ohmic electrode **160***a* may have first extension parts **165***a*, and the first Schottky electrode **170***a* may have second extension parts **175***a*. The first extension parts **165***a* may extend toward the first Schottky electrode **170***a*, and the second extension parts **175***a* may extend toward the first ohmic electrode **160***a*. The first extension parts **165***a* and the second extension parts **175***a* may be alternately disposed in one direction. The second ohmic electrode **160***b* may have third extension parts **165***b*, and the second Schottky electrode **170***b* may have fourth extension parts **175***b*. The third extension parts **165***b* may extend toward the second Schottky electrode **170***b*, and the fourth extension parts **175***b* may extend toward the second ohmic electrode **160***b*. The third extension parts **165***b* and the fourth extension parts **175***b* may be alternately disposed in one direction. The third ohmic electrode **160***c* may have fifth extension parts **165***c*, and the third Schottky electrode **170***c* may have sixth extension parts **175***c*. The fifth extension parts **165***b* may extend toward the third Schottky electrode **170***c*, and the sixth extension parts **175***c* may extend toward the third ohmic electrode **160***c*. The fifth extension parts **165***c* and the sixth extension parts **175***c* may be alternately disposed in one direction. The fourth ohmic electrode **160***d* may have seventh extension parts **165***d*, and the fourth Schottky electrode **170***d* may have eighth extension parts **175***d*. The seventh extension parts **165***d* may extend toward the fourth Schottky electrode **170***d*, and the eighth extension parts **175***d* may extend toward the fourth ohmic electrode **160***d*. The seventh extension parts **165***d* and the eighth extension parts **175***d* may be alternately disposed in one direction.

The first connection pad **350***a*, the second connection pad **350***b*, a third connection pad **350***c*, and a fourth connection pad **350***d* may connect the diode device **100** and the piezoelectric device **200** to the diodes D**1**, D**2**, D**3**, and D**4**. The first ohmic electrode **160***a* and the fourth Schottky electrode **170***d* may be connected to the first connection pad **350***a* and then electrically connected to a third electrode **260** of the piezoelectric device **200**. The second ohmic electrode **160***b* and the third Schottky electrode **170***c* may be connected to the second connection pad **350***b* and then electrically connected to a fourth electrode **270** of the piezoelectric device **200**. The first Schottky electrode **170***a* may be electrically connected to the second Schottky electrode **170***b* through the third connection pad **350***c*. The third ohmic electrode **160***c* may be electrically connected to the fourth ohmic electrode **160***d* through the fourth connection pad **350***d*. The third connection pad **350***c* and the fourth connection pad **350***d* may be connected to an external circuit.

According to an embodiment of the inventive concept, a change of strain may be applied to a second lower nitride layer **210** of the piezoelectric device **200** by environmental changes such as vibration and pressure variation. Since the second lower nitride layer **210** may include a piezoelectric material, electric energy may be generated by extension and contraction of the piezoelectric material. The generated electric energy may be transferred to a second electrode structure **250** through a second 2DEG layer **215**, and the second electrode structure **250** may supply the electric energy to the diode device **100** by the first connection pad **350***a* and the second connection pad **350***b*.

According to an embodiment of the inventive concept, the diode device **100** which constitutes the bridge circuit and the piezoelectric device **200**, may be disposed on a substrate **10**.

Thus, the hybrid diode device **2** in which the diode device **100** is capable of converting the alternating current-type electric energy autonomously generated by the piezoelectric device **200** into the direct current type may be realized.

FIG. **7** is a circuit diagram of the hybrid diode device according to an embodiment of the inventive concept.

Referring to FIGS. **4** to **7**, the piezoelectric device **200** may be an input power source generating electric energy, and the diode device **100** may be a full-wave rectification circuit which rectifies and converts the alternating current-type electric energy generated by the piezoelectric device **200** into the direct current type. The first ohmic electrode **160***a* and the first Schottky electrode **170***a* may constitute the first diode D**1**, the second ohmic electrode **160***b* and the second Schottky electrode **170***b* may constitute the second diode D**2**, the third ohmic electrode **160***c* and the third Schottky electrode **170***c* may constitute the third diode D**3**, and the fourth ohmic electrode **160***d* and the fourth Schottky electrode **170***d* may constitute the fourth diode D**4**. The fourth connection pad **350***d* may be connected to a first point X**1**, and the third connection pad **350***c* may be connected to a second point X**2**. An output terminal may be disposed between the first point X**1** and the second point X**2**. When positive electric energy generated by the piezoelectric device **200** is applied to the diode device **100**, the second diode D**2** and the fourth diode D**4** may be turned on to apply the positive electric energy to the output terminal. When negative electric energy generated by the piezoelectric device **200** is applied to the diode device **100**, the first diode D**1** and the third diode D**3** may be turned on to apply the positive electric energy to the output terminal. Thus, when the piezoelectric device **200** may generate the alternating current-type electric energy, the diode device **100** may output the positive electric energy. The positive electric energy converted into the direct current by the diode device **100** may be transferred to the output terminal to supply the power to a capacitor C and a load R_L.

Unlike the described-above embodiment, the first to fourth diodes D**1**, D**2**, D**3**, and D**4** in the diode device **100** may not limited in direction. However, the first to fourth diodes D**1**, D**2**, D**3**, and D**4** may constitute the bridge circuit.

According to the embodiment of the inventive concept, the hybrid diode device in which the piezoelectric device and the diode device are integrated on the one substrate may be provided. Thus, the diode device may rectify the alternating current-type electric energy autonomously supplied by the piezoelectric device.

According to the embodiment of the inventive concept, the hybrid diode device may autonomously supply the power to reduce the number of processes for electrically connecting the power source to the diode device. Since the self-power providing piezoelectric device and the diode device that is the rectification conversion device are integrated on the one substrate, the hybrid diode device may be miniaturized and also decrease in manufacturing cost.

Although the embodiments of the inventive concept are described with reference to the accompanying drawings, those with ordinary skill in the technical field to which the inventive concept pertains will understand that the present disclosure can be carried out in other specific forms without changing the technical idea or essential features. Thus, the above-described embodiments are to be considered illustrative and not restrictive to all aspects.

What is claimed is:

1. A hybrid diode device comprising:

a first lower nitride layer disposed on a substrate and including a first 2-dimensional electron gas (2DEG) layer;

a second lower nitride layer extending from the first lower nitride layer to the outside of the substrate and including a second 2DEG layer;

a first upper nitride layer disposed on the first lower nitride layer;

a second upper nitride layer disposed on the second lower nitride layer;

a first cap layer disposed on the first upper nitride layer;

a second cap layer disposed on the second upper nitride layer;

a first electrode structure connected to the first lower nitride layer and the first cap layer; and

a second electrode structure connected to the second lower nitride layer and the first electrode structure,

wherein the second lower nitride layer generates electric energy through dynamic movement and supplies the generated electric energy to the first electrode structure via an electrical connection between the first electrode structure and the second electrode structure.

2. The hybrid diode device of claim **1**, wherein the first 2DEG layer is spaced apart and electrically insulated from the second 2DEG layer.

3. The hybrid diode device of claim **1**, wherein each of the first and second lower nitride layers comprise gallium nitride (GaN) as a gallium nitride-based material.

4. The hybrid diode device of claim **1**, wherein each of the first and second upper nitrides comprise aluminum gallium nitride (AlGaN) as a gallium nitride-based material.

5. The hybrid diode device of claim **1**, wherein the first electrode structure comprises:

a first electrode electrically connected to the first 2DEG layer in the first lower nitride layer; and

a second electrode connected to the first cap layer,

wherein the second electrode structure comprises a third electrode and a fourth electrode, which are electrically connected to the second 2DEG layer in the second lower nitride layer.

6. The hybrid diode device of claim **5**, wherein each of the first electrode, the third electrode, and the fourth electrode is an ohmic electrode, and

the second electrode is a Schottky electrode,

wherein the third electrode is connected to the second electrode through a connection pad, and

the first electrode and the fourth electrode are connected to an external circuit.

7. The hybrid diode device of claim **5**, wherein the first electrode is an ohmic electrode that is provided in plurality, and

the second electrode is a Schottky electrode that is provided in plurality,

wherein the ohmic electrode that is provided in plurality and the Schottky electrode that is provided in plurality constitute a bridge circuit.

8. The hybrid diode device of claim **7**, wherein the ohmic electrode that is provided in plurality comprises a first ohmic electrode, a second ohmic electrode, a third ohmic electrode, and a fourth ohmic electrode,

the Schottky electrode that is provided in plurality comprises a first Schottky electrode, a second Schottky electrode, a third Schottky electrode, and a fourth Schottky electrode, and

a pair of the first ohmic electrode and the first Schottky electrode, a pair of the second ohmic electrode and the second Schottky electrode, a pair of the third ohmic electrode and the third Schottky electrode, and a pair of the fourth ohmic electrode and the fourth Schottky electrode constitute first to fourth diodes, respectively.

9. The hybrid diode device of claim **8**, wherein an isolation area is provided between the first to fourth diodes to respectively divide the first to fourth diodes into from each other.

10. The hybrid diode device of claim **8**, wherein the first diode and the fourth diode are connected to the third electrode through a first connection pad,

the second diode and the third diode are connected to the fourth electrode through a second connection pad, and

the first diode and the second diode, and the third diode and the fourth diode are connected to an external circuit through a third connection pad and a fourth connection pad, respectively.

11. A hybrid diode device comprising:

a first lower nitride layer disposed on a substrate and including a first 2-dimensional electron gas (2DEG) layer;

a second lower nitride layer extending from the first lower nitride layer to the outside of the substrate and including a second 2DEG layer;

a first upper nitride layer disposed on the first lower nitride layer;

a second upper nitride layer disposed on the second lower nitride layer;

a first cap layer disposed on the first upper nitride layer;

a second cap layer disposed on the second upper nitride layer;

a first electrode structure connected to the first lower nitride layer and the first cap layer; and

a second electrode structure connected to the second lower nitride layer and the first electrode structure,

wherein the second lower nitride layer generates electric energy through dynamic movement,

the second upper nitride layer comprises nitride layer patterns exposing a portion of the second lower nitride layer, and

the second 2DEG layer is provided on an area on which the second lower nitride layer contacts the nitride layer patterns.

12. The hybrid diode device of claim **11**, wherein the second 2DEG layer is discontinuously provided on an interface between the second lower nitride layer and the second upper nitride layer in a first direction, and

the first direction is perpendicular to a direction that is directed from the second upper nitride layer toward the second lower nitride layer.

13. The hybrid diode device of claim **11**, wherein the second electrode structure passes through each of the nitride layer patterns to contact the second 2DEG layer.

14. A hybrid diode device comprising:

a substrate comprising a body part and a cantilever;

a lower nitride layer disposed on the substrate and including a 2-dimensional electron gas (2DEG) layer;

an upper nitride layer disposed on the lower nitride layer;

a first isolation area configured to divide the 2DEG layer into a first 2DEG layer and a second 2DEG layer and divide the upper nitride layer into a first upper nitride layer and a second upper nitride layer;

a first electrode structure connected to the first 2DEG layer and the first upper nitride layer; and

a second electrode structure connected to the second 2DEG layer,

wherein the second 2DEG layer and the second upper nitride layer are disposed on the cantilever,

wherein the second electrode structure transfers electric energy, which is generated by a change of strain applied to the lower nitride layer, to the first electrode structure.

15. The hybrid diode device of claim **14**, wherein the first isolation area is recessed from the upper nitride layer toward the lower nitride layer.

16. The hybrid diode device of claim **15**, further comprising a connection pad disposed on the first isolation area,

wherein the connection pad connects the first electrode structure to the second electrode structure.

17. The hybrid diode device of claim **14**, further comprising a second isolation area which is recessed from the first upper nitride layer toward the first 2DEG layer to divide each of the first 2DEG layer and the first upper nitride layer into four parts,

wherein the first electrode structure comprises a pair of an ohmic electrode and a Schottky electrode, which are respectively connected to the divided first 2DEG layers and the divided first upper nitride layers.

18. The hybrid diode device of claim **17**, wherein the pair of the ohmic electrode and the Schottky electrode, which constitutes one diode, are provided in four, and

the pair of the ohmic electrode and the Schottky electrode provided in four constitute a bridge circuit.

19. The hybrid diode device of claim **14**, further comprising a cap layer disposed on a top surface of the upper nitride layer,

wherein the cap layer is divided by the first isolation area.

20. The hybrid diode device of claim **14**, further comprising a proof mass disposed on an edge of the cantilever facing the substrate,

wherein an opened space in which the cantilever is movable is provided below the cantilever.

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